EF01: Higgs Boson Properties

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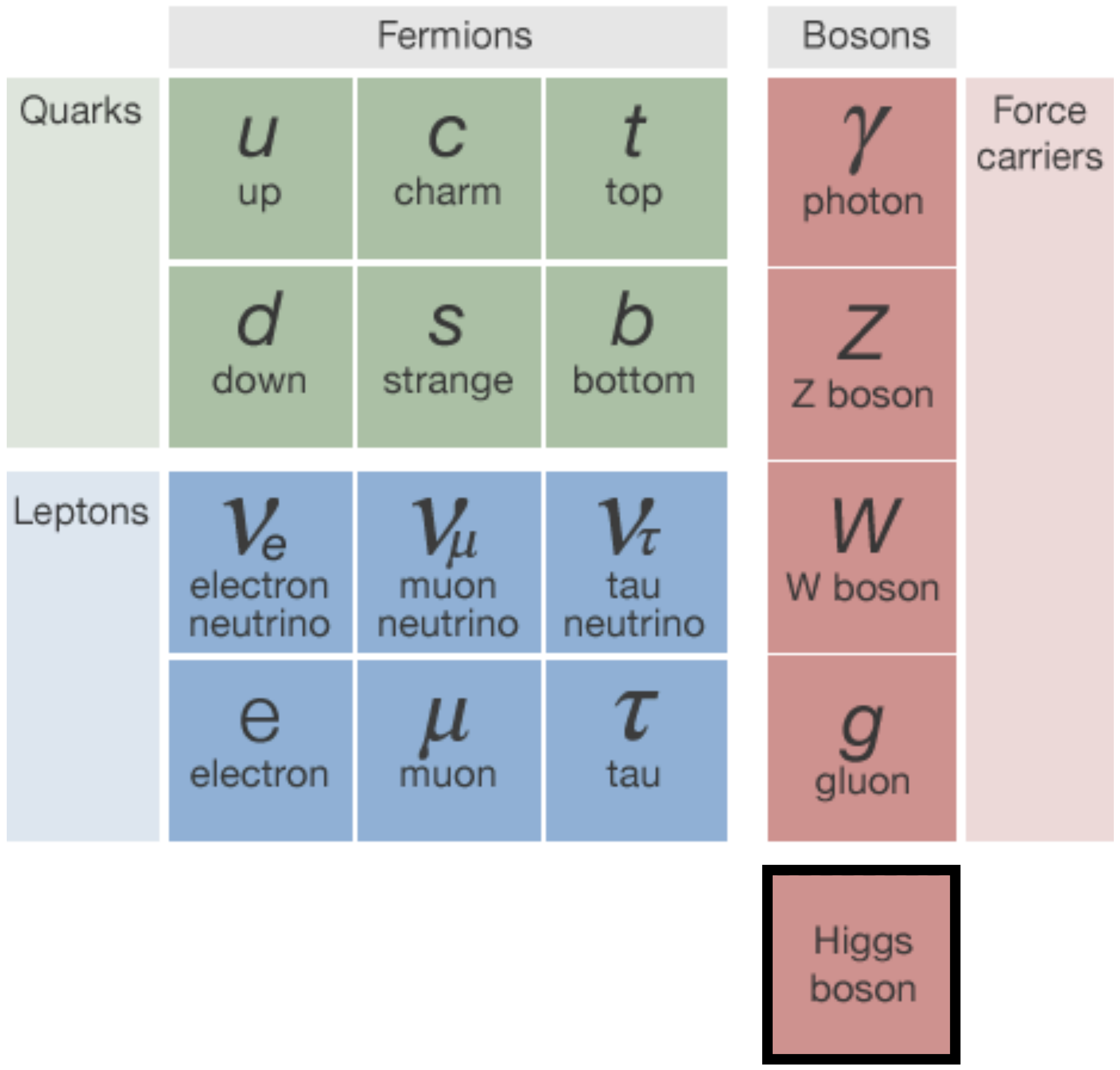
Snowmass21 EF Workshop: Open Questions and New Ideas

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

The Standard Model and Beyond



- The Standard Model is not a complete theory
  - gravitation, neutrino mass, dark matter …
- The Higgs boson is a **potential window to probe physics Beyond the Standard Model**
  - Searches for additional scalars
  - Precision measurements of the **Higgs boson properties**

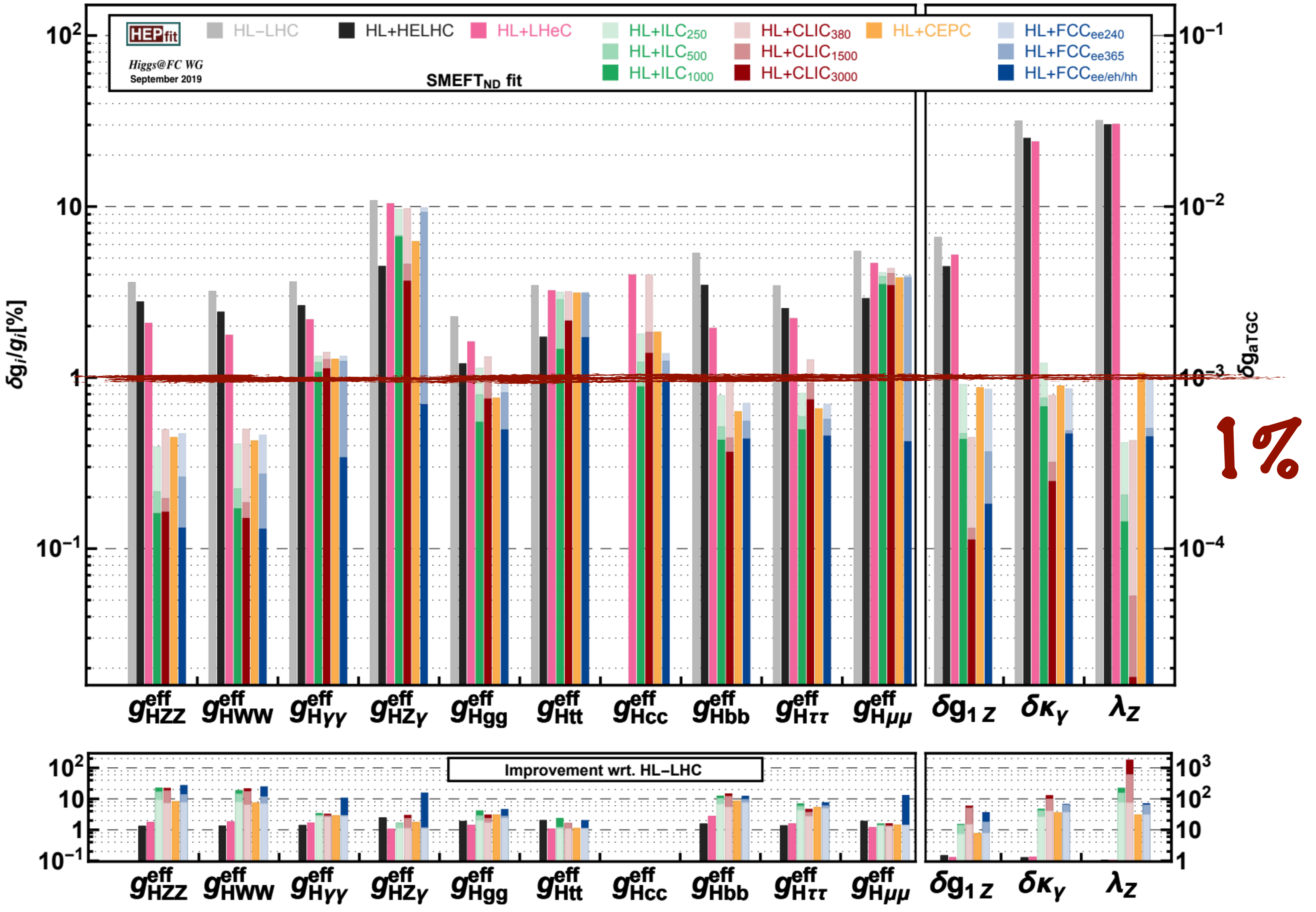
Higgs physics at future colliders

- The goal is to measure Higgs boson couplings with extremely good precision to unveil new effects beyond the Standard Model
  - We want to examine physics sensitivities as a function of the Higgs coupling precisions.
- Achieving **O(few%) level or below** precision will require high energy collider experiments designed to reduce systematic errors:
  - Need to produce O(100k) Higgs bosons
- Complementarity between $e^{+}e^{-}$ and p-p machines will eventually lead to the most precise understanding of the Higgs couplings
  - ***In particular, we need to prioritize what we want to learn on top of what HL-LHC will deliver?***
  - ***Timelines matter.***

Higgs projections from the ESG

ESG Higgs summary at Snowmass from C. Grojean
arXiv:1910.11775, arXiv:1905.03764, arXiv:1910.00012

- We have had overview talks from the main ESG's players and collected their feedback on what would be important to follow up during this year process.
- Future collider under consideration will improve wrt HL-LHC the understanding of the Higgs boson couplings- 1-5%
  - At low energy top-Higgs coupling is not accessible at future colliders
  - HL-LHC does not probe Higgs-charm
  - Couplings to μ/γ/Zγ benefit the most from the large dataset available at HL-LHC and not really improved at future colliders
- **Complementarity between HL-LHC and future colliders** (depending on their timeline) **will be the key to explore the Higgs sector**



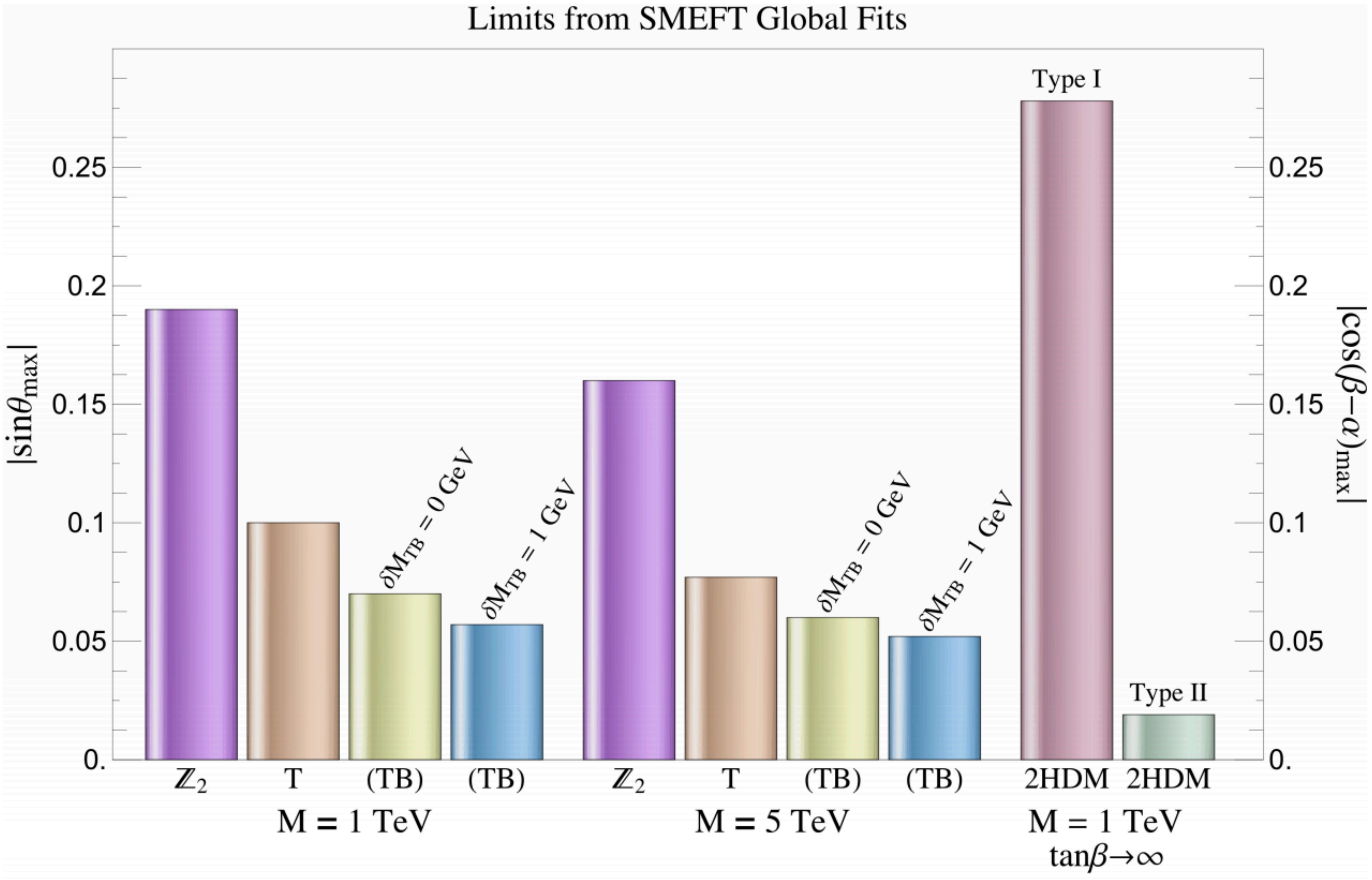
Defining Higgs priorities

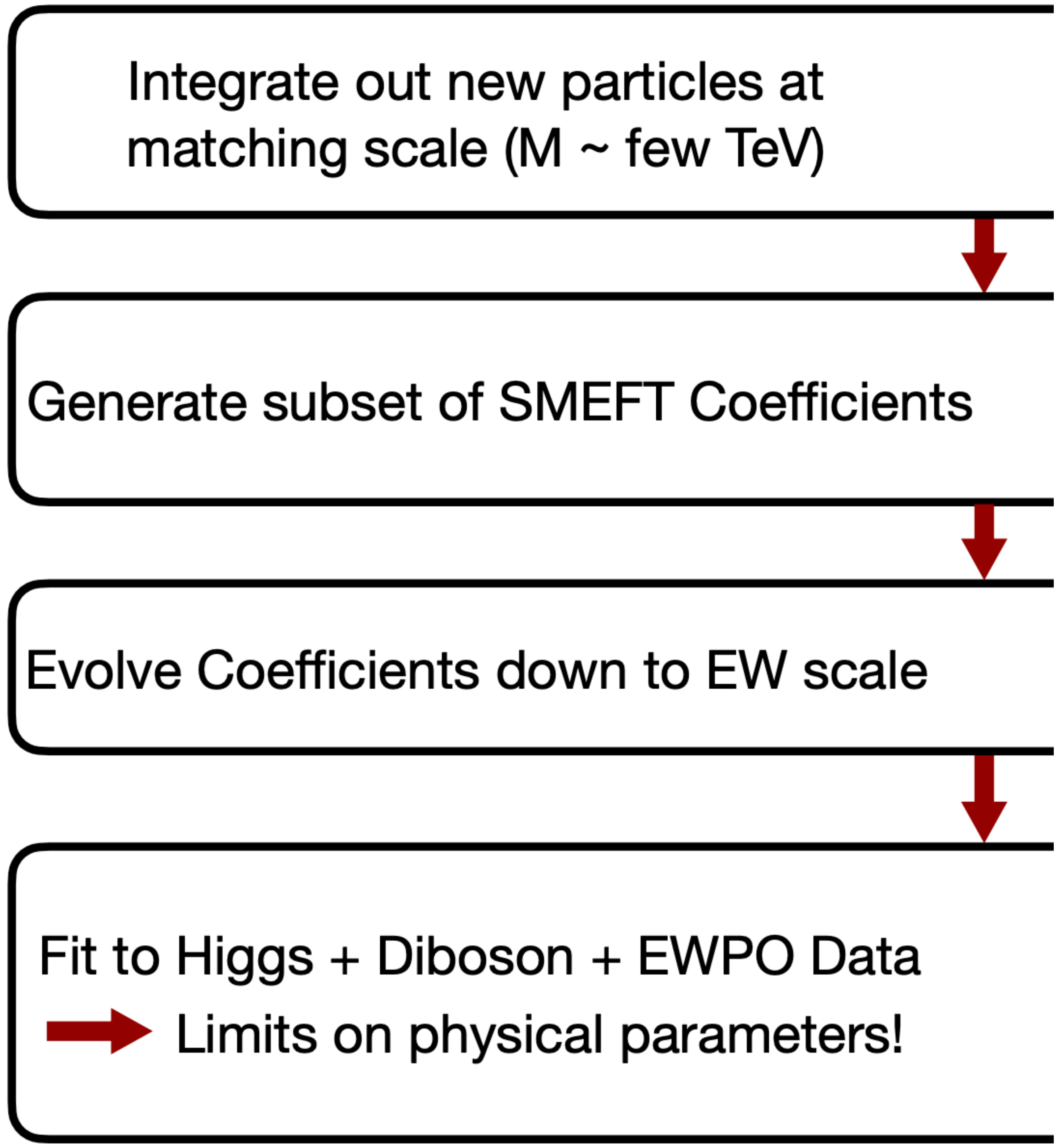
- An important question to explore is the **targets for precision measurements within the Higgs sector**.
  - At what precision is information about various scenarios uncovered?
  - We need to **define benchmark models** where detailed comparisons can be made between the capabilities of various facilities.
- Some of the **Snowmass21 Higgs studies that have emerged from the first meetings** :
  - Use of distributions at high Q^2 and measurements of ratios to reduce the impact of systematic effects
  - Measurement of the Higgs width and the inclusion of Higgs width effects in precision measurements
  - Developing a framework for determining the couplings to first and second generation quarks
    - The Higgs Boson coupling to electrons is a clear milestone.
- Develop a framework to evaluate how **EW/top/Higgs** measurements in different SM sectors contribute to the overall understanding.
  - This can optimally be done within an effective field theory framework - **in collaboration with EF04**
- The experimental understanding of the Higgs properties relies on the underlying theory framework.
  - We intend to develop **a list of needed theory calculations** corresponding to various machine and luminosity options.

An example from July 7-8 workshop

arXiv:2007.01296

- Talk from S. Homiller shows preliminary results on how to map BSM models to SMEFT constraints
  - Top data and NLO effects to be included in future iterations





$$
\begin{aligned}
\mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi \\
& + \psi_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi) = -\mu^2 \phi^2 + \lambda \phi^4
\end{aligned}
$$

Probing this Higgs Boson potential

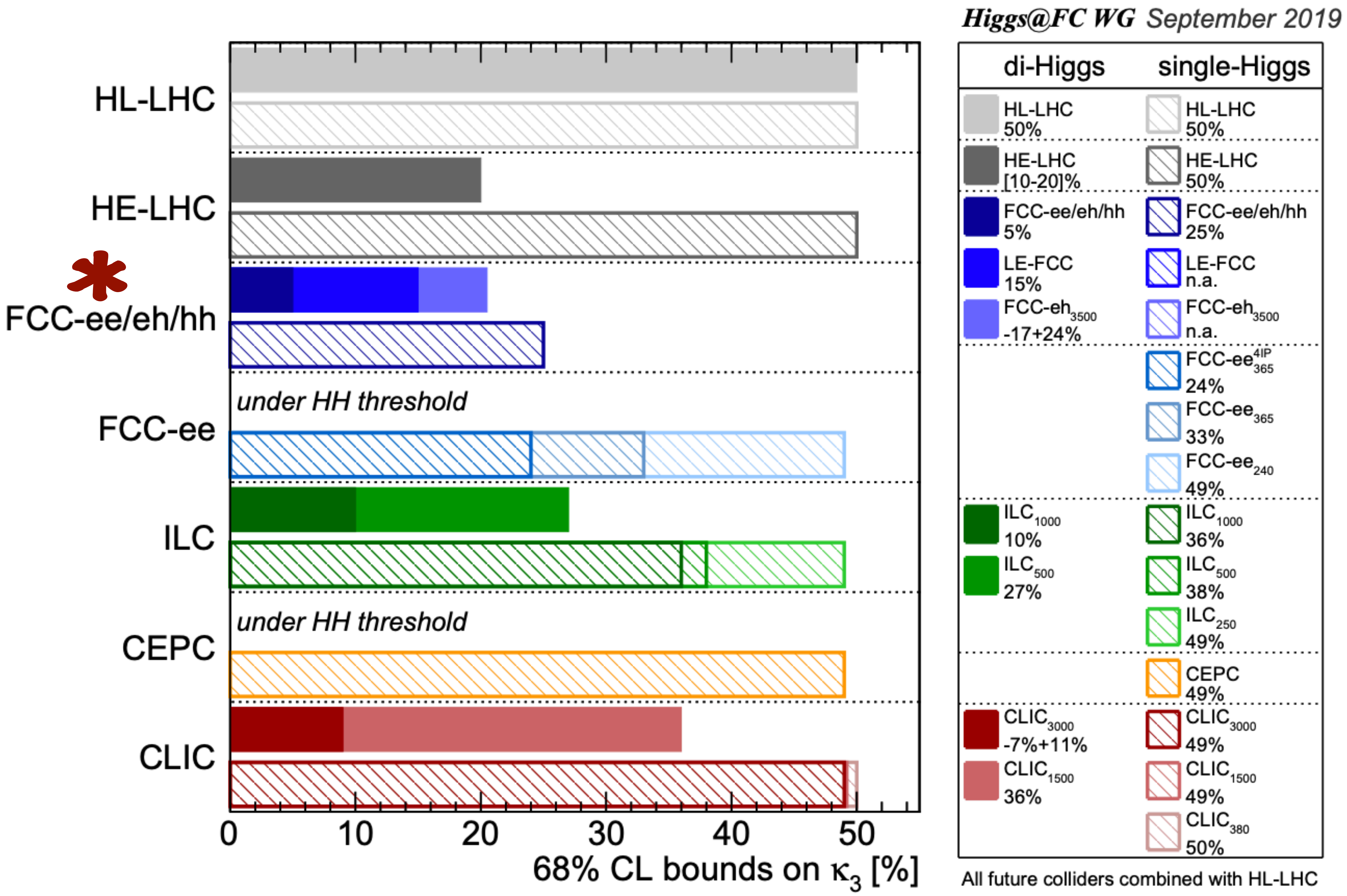
The Higgs Boson potential

- At the present time, we have no experimental evidence that the Higgs boson results from the scalar potential of the SM
    - Observing double Higgs Boson production is crucial.
- **Precision measurements of double Higgs** boson production can then be combined **with single Higgs** measurements for a better understanding of the structure of the Higgs potential.
- Models of **new physics that contain multiple Higgs bosons** can lead to the production of Higgs bosons with different masses, leading to new experimental signatures.

Higgs self-coupling

arXiv:1910.00012
arXiv:1905.03764

The goal for **future machines** beyond the HL-LHC should be to measure with good precision the Higgs boson self-coupling



collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
CEPC_{240}	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
CLIC_{380}	50%	–	50%
CLIC_{1500}	49%	36%	29%
CLIC_{3000}	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
* FCC-hh	-	5%	5%

μ-collider for HH : 7/3.5/1% at 6/10/30 TeV LianTao Wang's talk

* arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions

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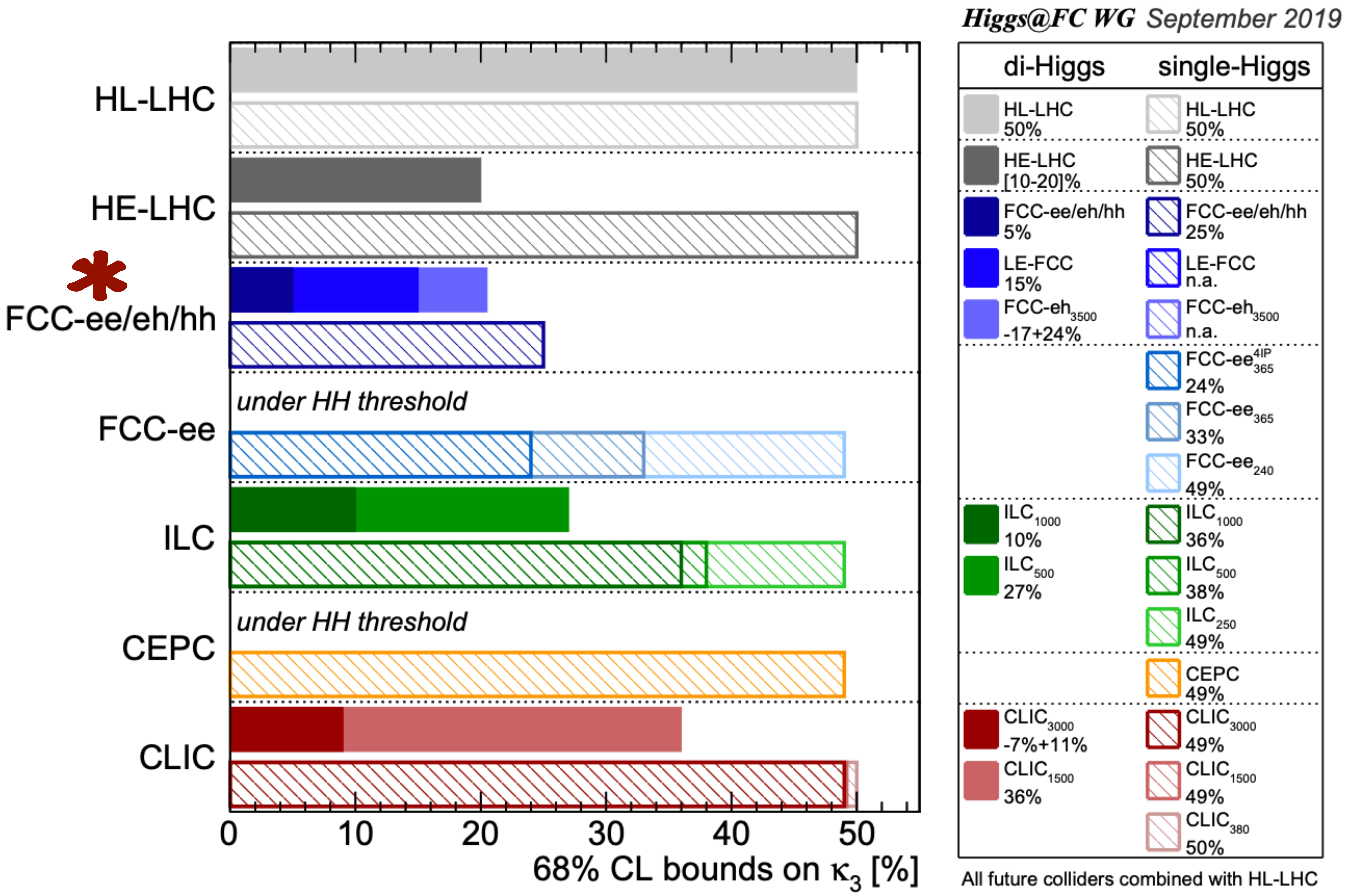

conservative?

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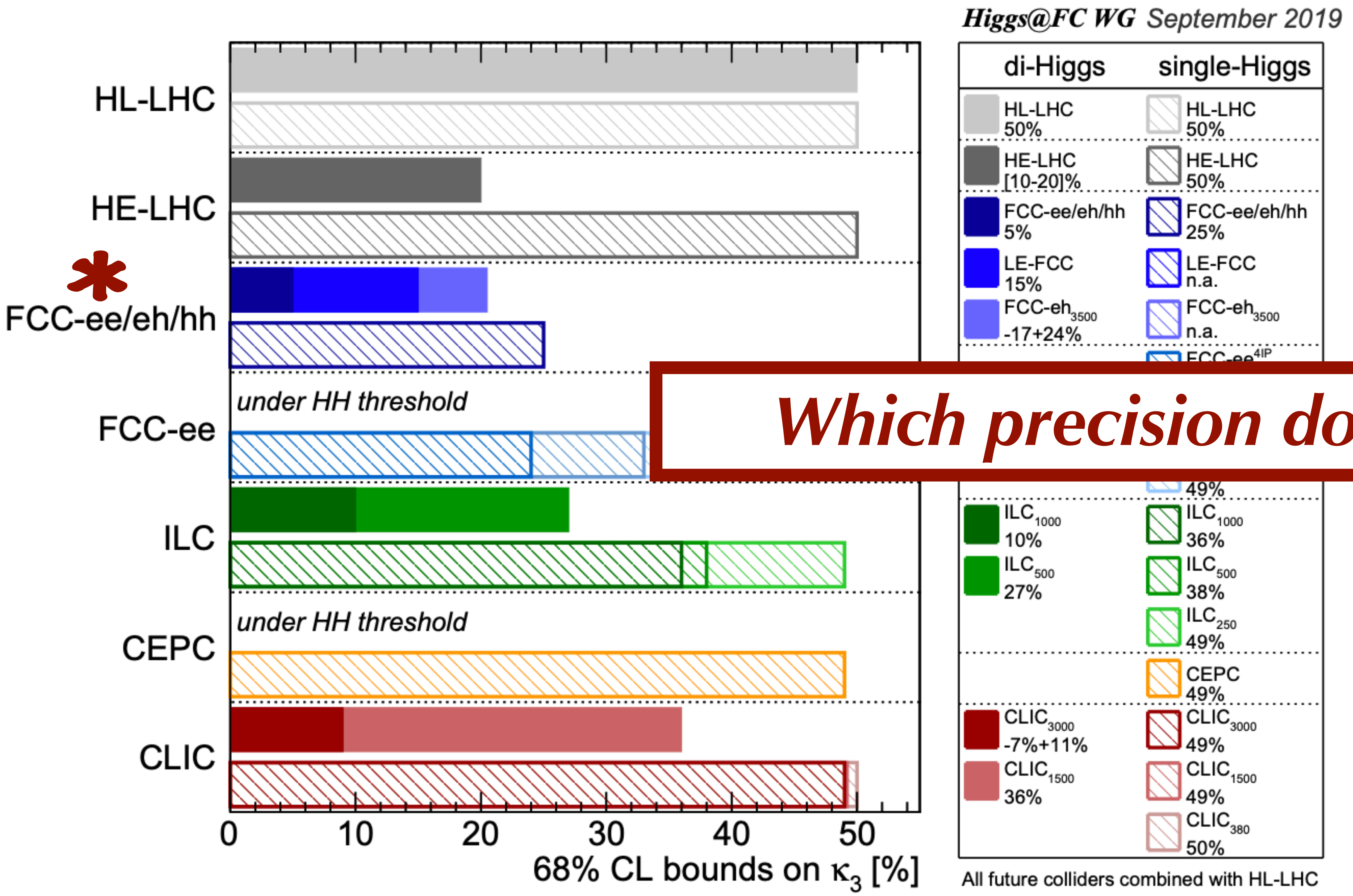

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Which precision do we need to aim for ?

* arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions

Which precision on the self-coupling is needed?

BRONZE 100%

SILVER 25-50%

GOLD 5-10%

PLATINUM 1%

Sensitivity to models with the largest new physics effects, in which new particles of few hundred GeV mass appear in tree diagrams or as s-channel resonances

Sensitivity to mixing of the Higgs boson with a heavy scalar with a mass of order 1 TeV. Models of electroweak baryogenesis typically predict this level of deviation in the trilinear Higgs self-coupling.

Sensitivity to a broad class of loop diagram effects that might be created by any new particle with strong coupling to the H. This could possibly complement measurements on new particles that could be discovered at the HL-LHC.

Sensitivity to typical quantum corrections to the Higgs self-coupling generated by loop diagrams

EF01 - Our work-in-progress to-do-list

- **Which physics beyond the Standard Model can be probed by precision measurements of Higgs couplings?**
  - How precise do these measurements need to be in order to probe BSM physics scenarios?
  - How are direct searches for new Higgs-like particles complementary to precision Higgs coupling measurements
    - This should be study by exploring the complementarity between HL-LHC and future colliders (accounting for their different timelines).
- Does the Higgs boson result from the scalar potential of the Standard Model?
  - How can measurements of double Higgs boson production be improved to better probe the potential ?
  - Which is the target precision for this? - taking into account the correlations with the other Higgs measurements
- How can measurements in the Higgs sector be combined with measurements in other sectors to improve our understanding of high scale physics?
- What theory calculations are needed to enable the theory precision to match the projected experimental precision of future measurements?

Next EF01 meeting, August 5

spares

Collecting expressions of interest

- We have held 3 meetings (one joint with EF02)
  - Next one after the workshops on August 5
  - We have had overview talks from the main ESG's players and collected their feedback on what would be important for Higgs studies during this year process
    - Used as input for the overleaf document
- About 20 replies to the google form:
  - Many about **HH at colliders** : we have them collected them and first "work" chat today (7/6)
    - Created dedicated slack-channel and will setup an email-list (fnal/cern?) - next meeting on 7/27 to finalize LOIs.
  - We have setup **common github/gitlab repositories** for people to share source files and the compiled table for any relatively well-defined topic, so it may be a more general repository, with sub-directories per topic
    - https://gitlab.cern.ch/snowmass21-ef01

HH & self-coupling

- We will review both **resonant and non-resonant DOUBLE HIGGS PRODUCTION**
  - Any missing experimental studies and unexplored signatures?
    - For resonant: production of different-mass Higgs bosons?
    - **Synergy with EF02 on resonant HH production** : is there any new physics effect that demands a dedicated analysis or signature based analyses are enough?
  - *There is a new FCC-hh study, shall we expect updates from HL-LHC based on full Run 2 analyses?*
    - **VBF HH** not really covered for HL-LHC but first Run 2 results are now available - opportunity for hadronic machines
    - Significant improvements are possible in the context of ILC (M. Peskin)
- For the self-coupling constraints it is important to consider effects on the other Higgs couplings
  - Revise how to optimally combine double Higgs and single Higgs data:
    - ex: differential information, different center of mass of energies for e^+e^- colliders
- Beyond HH: **HHH & quartic coupling?**

Higgs & (SM?)EFT

see also C. Grojean's talk

- **We will be working closely together with EF04 within the SMEFT framework:**
  - Estimate EFT uncertainties (NLO, dim-8 effects, linear vs quadratic…), new physics in backgrounds, theoretical constraints (positivity, analyticity)
  - More combined Higgs and top analysis
    1. effects of top dipoles or 4 fermion ops. with tops
    2. constraints on top EW couplings from their NLO effects in Higgs and diboson processes (particularly relevant for low-energy colliders below ttH threshold)
  - Include differential observables
  - Explore more flavor scenarios (and make connection with flavor data)
- SMEFT is a baseline, how we account for specific assumptions and model-dependency?
  - Complementarity with new physics searches